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Problems with Accurate Atomic Lifetime Measurements of Multiply Charged Ions

E. Träbert

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achieved decades ago [1, 2]; these calculations have been corroborated by experiments up outside of nominally closed atomic shells), for which very good calculations have been reduces the gap between calculations for a single-electron system (or a single electron is very notable recent progress in terms of the accuracy of *ab initio* calculations that knowledge elsewhere? Well, the atomic structure knowledge is, in fact, patchy. There and we can turn away from fundamental atomic physics in favour of applying the precision. Surely everything worth knowing about atoms is known with high precision, uncerainty level of 10^{-12} to 10^{-15} , and work continues that aims for even higher years. Nobel prizes have been awarded for atomic physics work at the relative 60 (Dirac equation) since more than 70 years, quantum electrodynamics (QED) for about mechanics (QM) has been with us for more than 80 years, relativistic quantum mechanics into each other and into A values, if the transition energies are known. Quantum emission of light by atoms; oscillator strengths f and fine strengths S can be converted Einstein A and B values describe the spontaneous and stimulated absorption and ionization) - Atomic lifetimes - Oscillator strengths - Visible and ultraviolet spectra.

1. Introduction

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Electronic excitation and ionization of atoms (including beam-foil excitation and ionization) - Atomic lifetimes - Oscillator strengths - Visible and ultraviolet spectra.

Abstract. A number of recent atomic lifetime measurements on multiply charged ions have reported uncertainties lower than 1%. Such a level of accuracy challenges theory, which is a good thing. However, a few lessons learned from earlier precision about the systematic errors of experimental techniques.

E-mail: traeber@astro.rub.de

U.S.A.

Astrophysics Institute, Ruhr-Universität Bochum, D-44780 Bochum, Germany, and Physics Division, Lawrence Livermore National Laboratory, Livermore CA 94550,

E. Traeber

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on the three-electron ion could be interpreted in terms of the corresponding entities in required calculations to match the high measurement precision so that the data obtained of the two-loop Lamb shift measured in the Li-like ion U_{89+}^{+} ; this, however, has outside closed shells (Li-, Na-, Cu-like ions), as in the example of the best measurement it has turned out to be advantageous experimentally to study a system with one electron pursued for which theoretical predictions are considered to be nearly perfect. Sometimes much can be learned. It is for this reason that one-electron atomic systems have been either theory or experiment on a given topic are insufficiently developed, not

one hand and to experiment on the other.

This ‘barrier’, recently, and promptly problems have surfaced that relate to theory on the an electron beam ion trap), specifically for highly charged ions, have broken through a rarely-meet challenge for decades. New techniques (using a heavy-ion storage ring or a rare-gas-metastable atom trap), but presently they have their own limits on precision that are beyond the scope of this Comment. I will use a figure of merit of 1% as a marker for precision in this discussion on atomic level lifetimes. This level of precision has been for precision in atomic structure physics [5], but presently they have their own limits on atomic structure physics, however, are also a measure of performance of decay. Accurate branching fractions, however, are also a deal with such unbranched decays. Only in the case of unbranched decays can the lifetime be inverted to yield a single value. Many precision lifetime measurements in fact deal with such unbranched difficulties. Experiment usually determines the total decay rate R of an atomic level k probabilities, that is, on Einstein A values. Here theory and experiment have similarly difficulties, however, even poorer is the reliability of predictions and data on transition probabilities, that is, on Einstein A values.

$$r_e = 1 / \mathbb{E}(A_e^{\text{in}}).$$

regularly in the form of a level mean life τ

$$R_{\text{tot},e} = \mathbb{E}(A_e^{\text{in}})$$

to all other (lower) levels j :

However, even poorer is the reliability of practical implementation of the QM part. Level differences nowadays is considered to be under better control than the many-body of many-body systems into computer codes. The QED contribution to atomic levels and atomic structure is much further advanced than the practical implementation of the QM at present theory can't deliver that for arbitrary ions. The theoretical understanding of Level (astrophysical observations aiming at extrasolar planets need higher precision), and (because of the light source properties) largely rely on classical spectroscopy. There a carefully trapped particles, studies in other spectral ranges and on multiply charged ions visible range of the electromagnetic spectrum and in observations of atomic beams and higher capabilities for spectral resolution and frequency determination (mostly) in the than that of the original numbers. Notwithstanding laser spectroscopy with its much binding energies, for examples), the relative uncertainty of the difference is much to emerge only rather recently [4]. Atomic spectra, after all, relate to the differences of atomic level energies, and when taking the differences of large numbers (of electrons to $Z = 92$ [3]. Evidently the accuracy in the description of atomic systems with more

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It is striking how poor an overall lifetime uncertainty of 1% looks in comparison to lifetime data are mostly an intellectual challenge, checking on the validity of such models well as for the diagnostics of plasmas via collisional-radiative modeling. Highly precise precise atomic level lifetimes exists for the industrial optimization of light sources as width, but the actual lifetime value is of little interest. A practical interest in reasonably lifetime corresponds to a vanishingly small level width and thus a narrow spectral line designs of future frequency standards rely on very long lived levels. Here the long level let us see the emission of much longer lived levels, because they are not quenched. Some frequencies of low-density plasmas (tokamaks etc. in the laboratory, or the solar corona) line emission can be detected only from very short lived ions. The much lower collision collisions broaden the emission lines, and, from a high-density plasma, characteristic excitation process and ionization balance in fluorescent tubes. In high pressure lamps, dominate, although much-longer-lived (metastable) levels play important roles for the

In common gas discharge light sources, atomic levels with nanosecond lifetimes profit from experiences made with old ones.

working range is very different, maybe the interpretation of the new experiments can theory, and the earlier experiment vs. theory situation may be repeated. Although the of millisecond level lifetimes in multiply charged ions that do not agree with modern ions with atomic levels of nanosecond lifetimes. Recently there have been measurements with the above laser spectroscopic measurements concerned atoms and singly charged

some what more conservative error estimates [10, 11] survived unbeatem. intervening better calculations. Interestingly, some of the earlier measurements with approach using molecular states [15, 16] superseded the old data and corroborated the eventually, refined atomic beam experiments [12, 13, 14] and also a very different theory evolved and then cast doubts on the full quality of the early measurements. reach the small error bars of the Berlin experiment. Over the course of some 15 years, for example using laser-induced fluorescence in a stationary target [11], did not quite considered as being too simplistic to be possibly accurate. Other types of experiment, the mark - with the exception of the numerical Coulomb approximation, which was [9, 10] for which theory did provide numbers. Surprisingly, theory was found to be off decades. The experimenters therefore turned to atomic systems (Li and Na atoms) ($\pm 0.25\%$) [8]. However, there was no theory available to match this precision for several of the $6p$ level of Ba II ($\pm 1\%$) [7] and, a few years later, of the $6s6p$ $1P_1$ level of Ba I techniques to fast atom and ion beams and reported precise measurements of the lifetime single-electron U_{91^+} . In this case, the indirect evidence gathered experimentally from one-electron ions by almost an order of magnitude.

2. Historical notes

As an example, 35 years ago the Berlin group of H. J. Andra applied laser spectroscopic a three-electron ion was still more accurate than any direct energy measurements of single-electron U_{91^+} . In this case, the indirect evidence gathered experimentally from

Lasers are generally not suited to reach excited levels (from the ground state or a low-lying metastable level) in multiply charged ions, nor to produce and excite in a selective way multiply charged ions, levels of several decades, beam-selective spectroscopy (BFS) [19] was the foremost technique to be employed for lifetime foil spectroscopy (BFS) [19]. Laser excitation has been applied in a variety of experiments, such as metastable of rare gases (pre-excited in a discharge or in a collision cell), fast atomic beams (produced from fast ion beams by electron capture in a dilute gas), and excited gas leaking from a discharge vessel. In this way, the rates of a large number of electric dipole (E1) transitions have been measured with precisions in the range of a few percent [18]. However, with the exception of the alkali atoms, theory does not compete for E1-dominated level lifetimes of complex atoms at the accuracy level of below 1%, and hardly any experimental data challenge theory at this level.

Precise lifetime measurements on atoms and some on singly charged ions usually employ laser excitation (see [17]). Laser excitation has been applied in a variety of experiments, such as metastable of rare gases (pre-excited in a discharge or in a collision cell), fast atomic beams (produced from fast ion beams by electron capture in a dilute gas), and excited gas leaking from a discharge vessel. In this way, the rates of a few percent [18]. However, with the exception of the alkali atoms, theory does not compete for E1-dominated level lifetimes of complex atoms at the accuracy level of below 1%, and hardly any experimental data challenge theory at this level.

Problems with accurate atomic lifetime measurements of multiply charged ions not available in all spectral ranges.

Therefore near to the background level. If the level lifetime is measured in the form of an exponential decay curve, no symmetry argument is available to reduce the uncertainty of the fit. Exponential components are similar to each other, and the fitting of several such components (from blends of cascade repopulation) is a non-linear process and compounds the uncertainty. The reference time scale and the signal-to-noise ratio of a given detector are of utmost importance as well. Furthermore, good detectors are of a line width, a Lorentzian, a Gaussian, or a Voigt profile has to be fitted to a much more extensive data sample, most data points of which are far out in the wings and additional, for example, to a reference clock). If the lifetime is to be determined from data points. In contrast, atomic lifetime measurements carry the full uncertainty (in few measurement points and a fit of an almost arbitrary symmetric curve shape to the spectral line - relative to a well established calibration curve - often requires only a single point place within a small working range, the overall position of a symmetric requirement for accuracy is but moderate. In particular, the position of a symmetric number in transition frequency space) of which has been established by other means. This requires only a minute "correction" needs to be added, for which on its own the very simple reasons for this. The determination of the position of a spectral feature takes place within a small working range, the overall position (a very large number in transition frequency space) of which has been established by other means. Some wavelength determinations that have reached a level of 10-15. There are several

Beam-foil spectroscopy has largely been limited to E1 transitions (and some M1 and M2 transitions in more highly charged ions) with lifetimes in the range a few picoseconds to hundreds of nanoseconds. E1 transition rates yield information on atomic wave functions that supplement those from atomic energy levels alone. The E1 transition rate depends on the transition energy and an extra power of the level of interest, but also all cascades feeding the very same level are measured, may decay curves in which the components differ substantially in time constant. The ANDC technique (Arbitrarily Normalized Direct Cascades) [27] in which not only the decay of the beam only very few ions actually interact with the laser light on resonance at a given time. The cascades often have lifetimes of the same order of magnitude as the levels of interest, but multi-exponential fitting algorithms can analyze reliability only those levels of interest, but multicomponent fits can obtain a good fit even if there are only few ions interacting with the laser at a given time.

3. Transition types

For most ions with several electrons in the valence shell the practical determination of experimental lifetimes is hampered by the occurrence of cascade repopulation. Laser excitation of full-excited ions has been demonstrated (the ion-foil interaction was employed to first make ions of other levels that are being excited as well). Selective excitation of full-excited ions has much wider than the band width of a good laser, and in a monochromatic ion beam is much wider than the band width of a good laser, and therefore only very few ions actully interact with the laser light on resonance at a level of interest by the decays of other levels that are being excited as well. Selective excitation only very few ions actully interact with the laser light on resonance at a level of interest by the decays of other levels that are being excited as well. Selective excitation of full-excited ions has been demonstrated (the ion-foil interaction was employed to first make ions of other levels that are being excited as well). Selective excitation of full-excited ions has been demonstrated (the ion-foil interaction was employed to first make ions of other levels that are being excited as well). Selective excitation of full-excited ions has been demonstrated (the ion-foil interaction was employed to first make ions of other levels that are being excited as well). Selective excitation of full-excited ions has been demonstrated (the ion-foil interaction was employed to first make ions of other levels that are being excited as well). Selective excitation of full-excited ions has been demonstrated (the ion-foil interaction was employed to first make ions of other levels that are being excited as well).

Measurement is started with an accuracy of just a few percent.

Beam-foil data are available for a number of elements of this sequence, as well as life-time value for Ar II, but has not reached any further along the isoelectronic sequence. After the experimental fact) [22] has found reasonable agreement with the experimental times larger than the smallest - for a given element. A new calculation (alas, presented among the results of earlier calculations, some were up to five isoelectronic sequence. Among the results in the same ion or in neighboring ions along the life-time value for Kr II and Xe II). Earlier beam-foil experiments had reached uncertainties similarly in Kr II and Xe II. The present beam-foil experiment had reached uncertainties selectively excite its first level above the ground state, the $3s^2p^6\ 2S_{1/2}$ level [21] (and been performed by using monochromatized synchrotron radiation to ionize Ar and to measure lifetime measurement ($\pm 0.4\%$) on a singly charged ion has

which also changes under irradiation.

Loss of the fast ions in the exciter foil whose precise thickness is difficult to establish and less than 1%, and much of the limitation owes to the problem of determining the energy loss of the fast ions in the exciter foil whose precise thickness is difficult to establish and less than 1%, and the poor contrast in observations, and therefore they preclude the extension of that technique. Only very few BES lifetimes measurements have reached an uncertainty of structure intervals in multiply charged ions mean very high quantum beat frequencies and the atomic time reference were recorded in parallel. The usually much larger fine of primary interest, but through a filter for a different wavelength. Thus the decay signal

An accurate lifetime measurement of this type was first achieved at the Heidelberg heavy-ion storage ring TSR. In a stored beam of He-like ions (C_4^+ , N_5^+) the presence of excited ions in the rest frame of the ion source accelerated state, the ion can either autoionize and thus return to its previous condition, or stabilize radiatively and thus change its charge state, which is easy to detect by catching the ion on its now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is practically undisturbed. The Heidelberg lifetime measurements on C_4^+ and N_5^+ [31], later extended to B_3^+ ions, have reached accuracies of as good as 0.2%, for levels up to B_3^+ ions, one of the simplest atomic systems and thus a particularly fundamental case in atomic structure theory. A later dipole decay of the lowest triplet level in two-electron ions, one of the most complex systems and thus a particularity found in atomic structure theory. The dipole decay data test the calculations of a relativistic operator which enables a magnetic lifetime of as good as 0.2%, for levels up to B_3^+ ions, many milliseconds. The lifetime measurements on C_4^+ and N_5^+ [31], later extended to B_3^+ ions, have reached dipole fields of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system. Excitation and probing involve such small cross sections that the stored ion beam is now different trajectory in the next magnetic dipole field of the beam guidance system.

4. Relativistic M1 transitions

Conventional ion traps (of Klinger, Penning, or Paul type) have all been used for atomic lifetime measurements (for reviews, see [28, 29, 30]), but have not yielded atomic lifetime results with accuracies of 1%. This has been achieved only with a heavy-ion storage ring or an electron beam ion trap (EBIT). Both types of device are covered in some detail in the above reviews. The heavy-ion storage ring can be seen as an extension of the beam-folli scheme: after excitation (in the injector accelerator or by a laser), the beam travels in a roughly circular vacuum vessel and passes the detection zone (a photon detector or an electron target followed by a particle detector) over and over again. The actual ion beam energy is of little importance; since there is no displacement of mechanical components necessary in order to measure a decay curve, only electronic timing and a determination of the ion loss rate of the stored ion beam are required.

The observation volume before radiative decay has a chance to take place. The trapping techniques. Otherwise ions at thermal energies or higher would escape from the millisecond to second range. Their measurement necessitates the application of ion lower by several orders of magnitude, and the corresponding atomic level lifetimes are in E1 transition rates; in ions of low to moderate charge states, however, their rates are simple picture. In very highly charged ions, M1 and E2 transition rates compete with complex wave functions as well as relativistic effects in highly charged ions modify this insensitivity to this, as they connect levels with similar radial wave functions. However, a given term (E1-forbidden transitions, mostly M1 and E2 transitions) are supposedly "through the electric dipole operator". Transitions between fine structure levels of

At both TSR and the Livermore EBIT, lifetime measurements have also addressed more complex ions with transitions accessible with the use of photomultiplier tubes (PMT). With about 60 μA of C^{2+} ions in the storage ring, the PMT signal rate of the intercombination of the solar-blind PMT was less than 1 count per second. The maximum operating frequency of TSR is about 5 Hz, so that the shortest storage time intervals are about 200 ms. The signal count rate reaches a peak-to-tail ratio of better than 200, 10 ms; the accumulated decay curves reach the signal level of about 200 ms. The decay of this ion was about 10 counts per second [41], while the dark count rate decay of C^{2+} ions in the storage ring, the PMT signal rate of the intercombination of the solar-blind PMT was less than 1 count per second. The maximum operating frequency of TSR is about 5 Hz, so that the shortest storage time intervals are about 200 ms. The signal count rate reaches a peak-to-tail ratio of better than 200, 10 ms; the accumulated decay curves reach the signal level of about 200 ms. The decay of this ion was about 10 counts per second [41], while the dark count rate

5. Spin-changing E1 (intercombination) transitions

At the standard [38, 39, 40]. The mutual agreement of these calculations that presently render them with anywhere near the desired accuracy. The accurate lifetime results for light ions, the atomic lifetimes are so long that presently no experimental technique can measure them with typical uncertainty ranges of a few percent. For He and the neutral He to Xe^{52+} spanning about 15 orders of magnitude. The above results are by far the most accurate among them. For Ar and beyond, beam-foil and recoil ion beam measurements have typically reached uncertainties of a few percent. For He and the longest isolelectronic sequence studied for a particular level lifetime, the results for the He-like ions are part of perfect noise rejection.

The Heidlerberg TSR and Livermore EBIT lifetime data on He-like ions are part of quality also to the fact that in the X-ray range detectors can be operated with almost parameters in obtaining high accuracy in atomic lifetime measurements using storage rings or EBITs [37]. The lifetime measurements on X-ray transitions owe part of their reliability to the fact that in the vacuum is indeed one of the key ultra-high vacuum (UHV) Penning traps; control of the vacuum in an EBIT than in conventional cryogenic EBIT, the ion loss rates are much lower in an EBIT than in a beam recorded in order to accumulate a decay curve. Owing to the excellent vacuum in a is switched off, the ions remain trapped [36], and their delayed X-ray emission can be breeds ions of the desired charge state inside a Penning trap. When the electron beam the Livermore electron beam ion trap (EBIT). In these measurements, an electron beam (lifetimes from a few milliseconds to less than one microsecond), has been studied at

The same M1 transition, but in He-like ions of elements N through S [33, 34, 35] storage ring [32], but the 1.8 s lifetime could not be determined to better than about 2%.

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Heidelberg heavy-ion storage ring [47, 48, 49]. With the (better than 1%) extrapolation of measurements on isoselectronic ions at the in Fe X has also been measured there, the result being in agreement with theory and EBIT [46], and the comparable, but more difficult to measure crossionizing lifetime has recently been corroborated by an even more precise one at the newer Heidelberg lifetime measurement on (Al-like) Fe XVI [45]. The Livermore EBIT calculations by Vilks and Ishikawa [44] have matched the (0.6%) Livermore Mller-Plesset matched experimental data quality. For example, the multi-reference Mller-Plesset recently the first *ab initio* calculations of certain M I dominated level lifetimes have but the practical calculations had little quantitative predictive value. Only rather how to combine S and ΔE (by different powers of ΔE for different transition types), value. In a sense, theory had the predictive value of indicating the correct principle of a line strength S that was practically identical to the basic single-configuration limit transition energy ΔE by the experimentally determined one, and combining this with theoretical predictions fell within 1%, but only after replacing whatever calculated of about 2%, which was reached on B-like ions of Ar and neighboring elements. Lifetime measurements on transitions in the visible appeared limited to an accuracy of about 2%, often with small E2 admixtures, are the staple of plasma charged ions, usually M I (often with small E2 admixtures), that probably related to vacuum conditions under insufficient control, while the single Oxford EBIT lifetime measurement was corroborated. For a while, the Livermore EBIT that probably work at Livermore has indicated shortcomings of earlier attempts elsewhere systematic work in both astrophysics and terrestrial plasmas. The associated level lifetimes in a number of ions have been measured at TSR and at several electron beam ion traps. Similarity at TSR, with some small deviations from calculation, is an open question how to corroborate further the validity of the experimental technique (except for the PMT, the same basis apply as in the successful measurements on He-like ions) calculation effort has been spent on any of these other ions.

Intercombination transitions in several other atomic systems have been measured similar to those in the storage ring. Better calculations would be most welcome, too. or whether multi-electron ions are subject to extra influences in the storage ring or whether multi-electron ions are subject to extra influences in the storage ring environment. Better calculations would be most welcome, too.

Q, and they seem to be isoselectronically consistent (see [43]), but no similar massive experimental data for the same intercombination transition in Be-like ions B, N, and shortcomings in the calculation or in the experiment. There are additional less accurate small high-level discreteness in worth calculating about, whether there are uncorrected disagreements with the experiment by slightly more than the combined error bars. This and disagreements with the experiment by slightly justified uncertainty of as little as 0.5% functions [42] is quoted with an intrinsically justified uncertainty of as little as 0.5% calculation of this case, involving a massive effort of including some 200,000 wave any multiply charged ion at the time. A relativistic configuration interaction (RCI)

6. E1-forbidden transitions

In a second lifetime measurement at the Heidelberg EBIT, the Al-like ion Fe_{13+} (spectrally Fe XIV) was studied [46]. In a way this ion is similar in structure to the B-like ions, just with principal quantum number $n = 3$ instead of $n = 2$. The disagreement with theory came out as 1%, or about 10 standard deviations, and also two using electrostatic ion traps [53, 54], one using a heavy-ion storage ring [55], and one using the EBIT at Livermore [45]. All have reported lifetime results on the long side of theory. Unfortunately, the result obtained at a heavy-ion storage ring carried the life-time side of prediction. For Fe XIV there are four other measurements, all using electrostatic ion traps [53, 54], one using a heavy-ion storage ring [55], and one using the long life-time side of prediction.

In a series of systematic error checks, of course, range of systematic errors.

would be larger than conceded by the Heidelberg experiment team, who have run a wide unexplained discrepancy as a measure of systematic error of the measurement - which experiments in other places. In the present situation, without independent least measurements could somehow be corroborated, perhaps by other measurements or at least of this particular QED correction - if the experimental accuracy of the lifetime test at the Heidelberg EBIT [51], the lifetime measurement could serve as a valid accuracy at the Heidelberg energy value, which has been determined to extreme the experimental transition energy value, which has also been determined with such a QED rate correction in an ordinary atomic system. In combination with rate and thus also the level lifetime by about 0.45%. This represents the first test correction acts as a multiplier $(1 + 2\alpha/\pi)$ on the transition rate and affects the rate and thus also the level lifetime by about 0.45%. This EAMM paper by C Froese Fischer years ago, but had been largely overlooked. This EAMM magnetic moment of the electron (EAMM, or (g-2)) that had been mentioned in a However, there is a quantum electrodynamics (QED) correction for the anomalous interpretation as a measure of S .

This should be a minor problem. Alternatively, the lifetime measurement might be configuration mixing might affect S , but near the low end of the isoelectronic sequence, energy (where nature takes care of the QED level shift) with the fine strength S . Alternatively, one can return to basic principles, combining the experimental transition representations the state of the art. The QM result for the transition energy would be corrected for QED contributions, which have a 0.4% effect on the transition rate. The Heidelberg group had excellent theory support of their own; their own calculation energies - again, there is no particular predictive value in most of these calculations. Comparison of quality. Most of them furthermore rely on experimental transition carry no uncertainty estimate, and therefore they are outright useless for any such more than that (and lie on one side). However, as pointed out above, most calculations several (experimental) standard deviations, and the predictions themselves scatter by several percent, but what does the comparison of such an accurate result to theory mean? At face value, the measurement disagrees with all available calculational results, by achieving the same result, but what does the comparison of such an accurate result to theory mean? Heidelberg EBIT, with an error estimate of less than 0.1% [50]. This is a remarkable achievement, but what does the comparison of such an accurate result to theory mean? About 442 nm is almost ideal for detection by PMTs) has also been studied at the suited to precision measurements (it is easy to introduce into an EBIT, the wavelength

systematic error beyond the cascade problem which is traceable to specific long-lived (*Heidelberg*) disagreement of the order of 0.3 to 0.5% results from an uncorrected discrepancy would disappear. It is of much interest to find out whether the remaining by more than one standard deviation, but with the assumed cascade correction, the result [45] is the next precise, and it also deviates from the present state of prediction on M_1 transitions that claim such a small uncertainty of 0.1%. The Livermore EBIT precise lifetime measurements on B -like ions such as P^- , Mg^- , P_{-} , or Cl -like ions. Nevertheles, the highly systematricality from the available predictions. The discrepancy is smaller than in case of (*Al-like*) Fe^{XIV} ; once the latter was corrected (approximately) for the aforementioned precise lifetime measurements on B -like Ar^{XIV} (at the *Heidelberg* EBIT) [50] differ (*Al-like*) Fe^{XIV} ; once the latter was corrected (approximately) for the aforementioned precise lifetime measurements on B -like ions. N_{e^-} yet been identified in B^- , Mg^- , P^- , or Cl -like ions. Nevertheles, the highly have been identified in Si^- and S -like ions [57], but no comparable cascades lifetimes. Similar cascades appear in Si^- and S -like ions [57], but no comparable cascades milliseconds second lifetime while practically all other levels have picosecond and nanosecond heavy-ion storage ring concerns a βp level of nanosecond lifetime feeding a βp level of Al -like ions that has become apparent at the Al -like cascade situation in Al -like ions that has become apparent at the

peculiar cascade still be sufficient for a notable influence.

However, if the initial ion excitation is by ion-foil interaction, the overall reservoir may so that these continuum states should not contribute much to the actual decay curves, of high-lying levels beyond $n \approx 30$ or 40 are expected to be quenched by such fields, fields of the beam guidance magnets also as motional electric fields. The populations in highly charged ions. In a storage ring, the fast ions experience the magnetic dipole a reservoir of cascades after radiative recombination, which should be more prominent high-lying bound states, Nicolaidis [56] has pointed out low-lying continuum states as cascade contribution might need to be reconsidered. Beyond the usual cascades from [46, 50] cite an error that is smaller by an order of magnitude, and then the possibility of deduced a minor error contribution. However, the *Heidelberg* EBIT measurements calculated and in comparison to a 0.7% lifetime measurement then reported, it was of EBIT lifetime measurements at Livermore [45], but based on collisional excitation measurements and in calculation to a 0.7% lifetime measurement the *Heidelberg* EBIT measured a minor error contribution. Such a cascade repopulation effect has been discussed in the context error of about 0.1%. Evidently, this is a magnitude that matters in accurate lifetime orders of magnitude would be difficult to observe directly, but might cause a systematic error of 10% of the atomic lifetime sought, a cascade contribution that is weaker by two cascade repopulation after non-selective excitation. If one assumes for the beam-foil beam-foil spectroscopy, atomic lifetimes that appear too long usually suffer from

7. Cascade story

Largest error bar (and deviation of the mean from prediction) of the sample, although in many other experiments the heavy-ion storage ring results were to be most accurate. This observation may yield a clue to a possible (much smaller) systematic error in the corresponding EBIT measurements.

corners.

physics continue to provide surprises, at the high-accuracy level as well as in unexpected ion losses are unimportant on this time scale. However, lifetime measurements in atomic transitions promises high accuracy for the lifetime, especially as corrections for the measurement cascade and without much of a background problem, dozens of picoseconds). Without yield the resonance level lifetimes (which are in the range of observations that would be rather straightforward to turn this approach into a time-resolved elements. It should be noted that laser spectroscopy prepared Li-like Fe ions [60] and in similar ions of heavier transitions in Hamburg), where intense EUV light sufficed to selectively excite the resonance Laser in Hamburg), where intense EUV light sufficed to selectively excite the resonance been achieved by the Heidelberg EBIT group at the FLASH facility (Free-Electron Laser in Hamburg), where intense EUV light sufficed to selectively excite the resonance selective excitation of resonance levels in highly charged ions of various elements has least selective modulation of the population) of levels can suppress the cascade problem. Least selective principle, but adjusted to multiply charged ions, should do: selective excitation (or at been achieved by laser excitation of fast ion beams decades ago? Indeed, the same principle, but adjusted to multiply charged ions, should do: selective excitation (or at this case, theory does not even agree with the experimental result.

In certain cases, even some that are considered to be relatively simple. And in accuracy in certain cases, the uncertainty of this comment, but it underlines how difficult it will be to ascertain the 1% guideline of this comment, the result was given as 5%. This is some way from detection process; the uncertainty of the result was given as 5%. This is some way from employed a heavy-ion storage ring and dielectronic recombination, a highly selective about 20% from a very recent experiment on Be-like $_{47}^{47}\text{Ti}^{18+}$ ions [58]. The experiment Johnson [59] have come to predictions that differ by up to 80% from earlier ones, and by Johnson [59] have come to predictions that differ by up to 80% from earlier ones, and by satisfactory. In Be- and Mg-like ions, however, recent calculations by Cheng, Chen and for nearly 80 years. In He-like ions, the agreement of theory and experiment seemed example of hyperfine quenching. The effect has been conceptualized and understood problems be overcome, at least down to an accuracy of 0.5%? Not quite. Take the discrepancy between the EBIT results and theory clarified, will then all lifetime-related once the QED correction to the M1 transition operator is fully understood and the 0.5%

8. Note of caution

For example, on the nuclear charge or on the principal quantum number n . not found any theoretical presentation of this topic or whether the corrections depend, QED corrections may be applicable to other E1-forbidden transition rates, but we have Godetroid is now working on a tensor treatment of the M1 operator. Corresponding EBIT measurements apply to M1 transitions, and because of the above findings, Michel the deviation from highly developed theory [42] has the opposite sign). The Heidelberg transition in Be-like CII [41], no QED correction to a transition operator applies, and other highly precise measurement, a storage ring experiment on the intercombination levels, or whether this is a glimpse at new physics. (We note that for the aforementioned

- [1] Kim Y-K, Baak D H, Lindigkeit P and Declaux J P 1991 *Phys. Rev. A* **44** 148
- [2] Blundell S A 1993 *Phys. Rev. A* **47** 1790
- [3] Triebert E, Becker P and Chou H 2004 *Phys. Rev. A* **70** 082506
- [4] Vilka M J and Ishikawa Y 2005 *Phys. Rev. A* **72** 032512
- [5] Curtis L J, Federman S R, Tork S, Brown M, Cheng S, Irving R E and Scheitman R M 2007 *Phys. Scr. T75* C1
- [6] Becker P, Chou H, Thorin D B and Triebert E 2005 *Phys. Rev. Lett.* **95** 233003
- [7] Andra H J, Gaupp A and Wittmann W 1973 *Phys. Rev. Lett.* **31** 501
- [8] Andra H J 1976 in *Beam Foil Spectroscopy*, edited by I A Sellin and D J Pegg, New York: Plenum Press p. 835
- [9] Gaupp A, Kuske P and Andra H J 1982 *Phys. Rev. A* **26**, 3351
- [10] Schulz-Hagencott D 1979 PhD thesis, University of Kaiserlautern (unpublished) cited in [9]
- [11] Carlsson J 1988 Z. Phys. D **9** 147
- [12] Volz U, Majerus M, Ljubaš H, Schmidt A and Schmoranz H 1996 *Phys. Rev. Lett.* **76**
- [13] Volz U and Schmoranz H 1996 *Phys. Scr. T65* 48
- [14] Oates C W, Vogel K and Hall J L 1996 *Phys. Rev. Lett.* **76** 2866
- [15] McAlexander W I, Abraham E R I, Richtic N W M, Williams C J, Stoot H T C and Huillet R G 1995 *Phys. Rev. A* **51** R871
- [16] McAlexander W I, Abraham E R I and Huillet R G 1996 *Phys. Rev. A* **54** R5
- [17] Scholl J, Hoh R A, Mastoramis D, Rivest R C, Rosner S D and Sharikova A 2002 *Can. J. Phys.*
- [18] De Hartog E A, Lawler J E Sheden C and Cowan J J 2003 *Astrophys. J. Suppl. Ser.* **148** 543
- [19] Triebert E 1997 in "Accelerator-based Atomic Physics Techniques and Applications", (Edited by S M Shattock and J C Austin) (*Washington: Am. Inst. Phys.*) p. 567
- [20] Astner G, Curtis L J, Liljeby L, Manncrirk S and Marthinson I 1976 Z. Phys. A **279** 1
- [21] Lawler S, Ljubaš H, Vollwicht F, Schmoranz H, Lagutin B, Demekhin Ph V, Petrov I D and Sukhorukov V I 1999 J. Phys. B: At. Mol. Opt. Phys. **32**, 2015
- [22] Šabha B and Fitzsche S 2005 J. Phys. B: At. Mol. Opt. Phys. **38** 1161
- [23] Triebert E 1996 J. Phys. B: At. Mol. Opt. Phys. **29** L217
- [24] Bigmont E and Triebert E 2000 J. Phys. B: At. Mol. Opt. Phys. **33** 2939
- [25] Borrmgård K A, Pöhl J C and Waldeck J A 2001 J. Phys. B: At. Mol. Opt. Phys. **34** L419
- [26] Baumdickt-Robinet Y, Garin H-P, Dumont P-D and Brasileon J 1990 *Phys. Rev. A* **42** 1080
- [27] Curtis L J, Berry H G and Brodmann J 1971 *Phys. Lett. A* **34** 169
- [28] Triebert E 2000 *Phys. Scr. T61* 267
- [29] Triebert E 2002 *Phys. Scr. T100* 88
- [30] Triebert E 2002 *Phys. Can. J. Phys.* **80** 1481
- [31] Schmidt H T, Förck P, Grässer M, Habes D, Kammacher J, Mitterer G, Repnow R, Schramm U,
- [32] Triebert E, Gwinther G, Kyrestas E J and Wolf A 2003 *Can. J. Phys.* **81** 941
- [33] Crespo López-Urrutia J R, Becker P, Savin D and Widmann K 1998 *Phys. Rev. A* **58**

References

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- [34] Triebert E, Beiersdorfer P, Brown G V, Smith A J, Utter S B, Gu M F and Savin D W 1999 *Phys. Rev. A* **60** 2034
- [35] Crespo López-Urrutia J R, Beiersdorfer P and Widmann K 2006 *Phys. Rev. A* **74** 012507
- [36] Beiersdorfer P, Schwilkhard L, Crespo López-Urrutia J and Widmann K 1996 *Rev. Sci. Instrum.* **67** 3818
- [37] Triebert E, Beiersdorfer P, Gwinnett G, Pimplington E H and Wolf A 2002 *Phys. Rev. A* **66** 062507
- [38] Drake G W F 1971 *Phys. Rev. A* **3** 908
- [39] Lin C D, PhD thesis, Columbia University, New York 1975
- [40] Johnson W R, Ph.D. thesis, University of Washington, Seattle, Washington 1995 in *Advances of atomic, molecular and optical physics Vol 35*, edited by B. Bederson and H. Walther, San Diego: Academic Press, 255
- [41] Doerfler J, Triebert E, Wolf A, Schwalm D and Utter O 1997 *Phys. Rev. Lett.* **78** 4355
- [42] Chen M H, Cheng K T and Johnson W R 2001 *Phys. Rev. A* **64** 042507
- [43] Triebert E and Curtis L J 2006 *Phys. Scr.* **74** C46
- [44] Vilkes M J and Ishikawa Y 2003 *Phys. Rev. A* **68** 012503
- [45] Beiersdorfer P, Triebert E and Pimplington E H 2003 *Astrophys. J.* **587** 836
- [46] Beiersdorfer G, Crespo López-Urrutia J R, Hammann Z, Moller P H and Ulrich J 2007 *Phys. Rev. A* **75** 032504
- [47] Triebert E 2004 *Astrophys. Astrophy. A* **15** L39
- [48] Triebert E, Saathoff G and Wolf A 2004 *Can. J. Phys.* **37** 946
- [49] Triebert E, Reinhart S, Hoffmann J and Wolf A 2006 *Can. J. Phys.* **39** 945
- [50] Lapierre A, Crespo López-Urrutia J R, Braun J, Breuer G, Brumus H, Fischer D, Gonzales-Martinez A J, Mironov V, Osborn C J, Sikler G, Soita Orts R, Tawara H, Ulrich J, Shabacy V M, Tupper I I, Zhou Y and Ulrich J 2003 *Phys. Rev. Lett.* **91** 183001
- [51] Draegerle G, Crespo López-Urrutia J R, DuBois R, Fitzsch C, Shabacy V M, Soita Orts R, Tupper I I, Zhou Y and Ulrich J 2006 *(private communication)*
- [52] Johnson W R 2006 *(private communication)*
- [53] Moche D P, Bhatti M I and Chuich D A 2001 *Phys. Rev. A* **63** 032515
- [54] Smith S J, Chiyutina A and Losano J A 2006 *Phys. Rev. A* **72** 062504
- [55] Triebert E, Gwinnett G, Wolf A, Kyestautas E J, Gauthier H-P and Torodio X 2002 *J. Phys. B: At. Mol. Opt. Phys.* **42** 025002
- [56] Nicolaides C A 1977 *Phys. Lett.* **63 A** 209
- [57] Triebert E, Hoffmann J, Kraatz C, Wolf A, Ishikawa Y and Satohara J A 2009 *J. Phys. B: At. Mol. Opt. Phys.* **42** 025001
- [58] Schippeler S, Schmidt E W, Bernhardt D, Yu D, Miller A, Lestinsky M, Orlow D A, Gricev M, Epp S W, Crespo López-Urrutia J R, Breuer G, Mackel V, Moktar P H, Tousch R, Kuhlmann M, Yukov M V, Faddeevs J, Schmidler J R, Wallhoefer M, Martins M, Wurth W and Ulrich J 2007 *Phys. Rev. Lett.* **98** 183001